VERTICAL ELECTRICAL DOWNTILT ANTENNA

REFERENCE TO RELATED APPLICATIONS

This application incorporated by reference the disclosures of commonly owned United States Patent Application Serial Number 10/290,838 entitled "Variable Power Divider" filed on November 8, 2002; United States Patent Application Serial Number 10/226,641 entitled "Microstrip Phase Shifter" filed on August 23, 2002; and United States Patent Application Serial Number ____________________ entitled "Double-Sided, Edge-Mounted Stripline Signal Processing Modules And Modular Network" filed on July 18, 2003.

TECHNICAL FIELD

The present invention relates to wireless base station antennas systems and, more particularly, relates to an antenna using a beam steering circuit including a variable power divider and a multi-beam beam forming network to implement vertical electrical downtilt and sidelobe reduction. The antenna, which may be a dual-polarization antenna, may also include a power distribution network that implements beam tilt bias and further sidelobe reduction.

BACKGROUND OF THE INVENTION

The market for wireless base station antennas is highly price and performance competitive. For this reason, it is advantageous to develop antennas having functions that are suitable for use as wireless base station antennas, and that exhibit desirable initial and lifetime cost characteristics. At the same time, it is also desirable to outfit the antennas with a significant range of operational flexibility, so that a standard antenna design may be used for a wide range of potential antenna sites and feature preferences. Meeting these often conflicting design objectives is a continuing challenge for the designers of wireless base station antennas.

In particular, adjustable downtilt and sidelobe minimization are desirable characteristics for a wireless base station antenna. Conventional methods for implementing adjustable downtilt have included mechanical downtilt systems that rely

on manual or motorized bracket adjustment. Alternatively, conventional electrical downtilt systems typically rely on multiple beam steering phase shifters. These techniques are relatively expensive to implement. In addition, sidelobe minimization has conventionally been accomplished through relatively complicated antenna element spacing, power distribution, and phase control schemes. These techniques are also relatively expensive to implement.

Accordingly, there is an ongoing need for more cost effective systems for implementing beam tilt and sidelobe minimization for wireless base station antennas.

SUMMARY OF THE INVENTION

The present invention meets the needs described above in an antenna suitable for use as a wireless base station antenna that implements vertical electrical downtilt and sidelobe minimization. The antenna includes a multiple element array and a beam steering circuit including a variable power divider and a multi-beam beam forming network. The antenna also includes a power distribution network connecting the outputs of the beam steering circuit to the individual elements of the antenna array. The variable power divider may employ a single adjustable control element to divide an input voltage signal into a pair of complimentary amplitude voltage drive signals over a range of voltage amplitude division. In addition, the voltage drive signals may exhibit matched phase and constant phase delay through the variable power divider over the range of voltage amplitude division. This configuration produces voltage drive signals for controlling the electrical tilt without the need for multiple phase shifters or mechanical bracket adjustment systems.

The voltage drive signals are used as input signals for the multi-beam beam forming network, which produces a number of beam driving signals that each typically include a beam component associated with each voltage drive signal. Each beam driving signal, in turn, drives a sub-array including one or more antenna elements. As a result, the beam emitted from the antenna is a composite beam that exhibits a directional tilt that varies within a range of tilt in response to changes of the voltage amplitude division within the range of voltage amplitude division. This type of composite beam, which varies in direction in response to changing weighting of multiple component beams, exhibits lower sidelobes than a single-component beam steered though conventional phase control having the same number of adjustable control elements.

The antenna includes an array of antenna elements, which are typically spaced apart in a vertical column and organized into one or more inner sub-arrays located between outer sub-arrays. In addition, the number of antenna elements in the outer sub-arrays may be greater than the number of antenna elements in the inner sub-arrays for the purpose of reducing sidelobe emission. The power distribution network may also be configured to implement coordinated phase shifting of the beam driving signals delivered to the elements of one or more sub-arrays to cause a desired blurring of the phase matching of the signals emitted by antenna elements of the sub-array for the purpose of reducing sidelobe emission.

In addition, the beam forming networks may be implemented as double-sided, edge-connected modules mounted to a main panel, which carries the variable power divider, the power distribution network, and the antenna elements. This configuration produces a number cost and flexibility advantages associated with the modular double-sided, edge-connected construction technique. The various features described above may be included in different combinations and permutations to provide antennas with features and advantages that are suitable for a range of applications and feature preferences.

Generally described, the present invention may be implemented as an antenna system including an array of antenna elements defining a boresight direction. The antenna may include a variable power divider using a single adjustable control element to divide an input voltage signal into a pair of complimentary amplitude voltage drive signals over a range of voltage amplitude division. The voltage drive signals, which may exhibit matched phase and constant phase delay through the variable power divider over the range of voltage amplitude division, feed a beam forming network that produces a number of beam driving signals that typically include a beam component associated with each voltage drive signal. A power distribution network delivers each beam driving signal to one or more associated antenna elements, such that the beam driving signals drive the antenna elements to emit a beam exhibiting a directional tilt with respect to the boresight direction that varies within a range of tilt in response to changes of the voltage amplitude division.

The antenna may also include a number of additional features, such as a field adjustable tilt direction actuator for adjusting the voltage amplitude division and thereby adjusting the directional tilt of the beam. The antenna may also include a power distribution network that implements coordinated phase shifting of the beam driving signals delivered to the antenna elements to cause a desired tilt bias for the

range of tilt. The antenna may also include a field adjustable tilt bias actuator for adjusting the tilt bias, and a remote controller for controlling the field adjustable tilt direction actuator and/or the field adjustable tilt bias actuator.

The antenna elements are typically organized into one or more inner sub-arrays located between outer sub-arrays, and each beam driving signal drives an associated antenna sub-array. The number of antenna elements in the outer sub-arrays may be greater than the number of antenna elements in the inner sub-arrays for the purpose of reducing sidelobe emission. In a particular configuration, the number of outer sub-arrays may be two, the number of inner sub-arrays may be two, the number of antenna elements in each outer sub-array may be four, and the number of antenna elements in each inner sub-array may be two. In another particular configuration, the number of outer sub-arrays may be two, the number of inner sub-arrays may be two, the number of antenna elements in each outer sub-array may be five, and the number of antenna elements in each inner sub-array may be three.

In yet another particular configuration, the power distribution network implements coordinated phase shifting of the beam driving signals delivered to the elements of one or more sub-arrays to cause a desired blurring of the phase matching of the signals emitted by the sub-array for the purpose of reducing sidelobe emission. In this alternative, the number of outer sub-arrays may be two, the number of inner sub-arrays may be two, the number of antenna elements in each outer sub-array may be four, and the number of antenna elements in each inner sub-array may be four. Alternatively, the number of antenna elements in each outer sub-array may be three, and the number of antenna elements in each inner sub-array may be three.

The beam forming network is typically implemented as a two-by-four orthogonal beam forming network or as a four-by-four Butler matrix. In addition, each antenna element may be a dual-polarization antenna element, and the antenna system may include a similar variable power divider, beam forming network, and power distribution network for each polarization. In this case, the field adjustable tilt direction actuators may be mechanically linked to each other to adjust the beam tilt for both polarities in a coordinated manner. In addition, the power distribution network may implement coordinated phase shifting of the beam driving signals delivered to the sub-arrays to cause a desired tilt bias of the range of tilt for each polarization. In this case, the antenna system may also include a field adjustable tilt bias actuator for adjusting the tilt bias for both polarizations in a coordinated manner.

The antenna typically includes a substantially flat panel defining a longitudinal axis substantially perpendicular to the boresight direction. In addition, the panel supports the array of antenna elements in a spacing configuration having a substantially vertical distribution, and the array is divided into one or more inner sub-arrays located vertically between outer sub-arrays. The beam forming network may also be configured as a double-sided, edge-connected module mounted to the main panel.

The preceding design components may combined to create a number of different of vertical electrical downtilt antennas with different features suitable for a range of wireless base station applications and feature preferences. It should be understood that the features described above may be implemented in different combinations and permutations suitable for particular applications. That is, the present invention contemplates providing a number of antenna features that may be mixed and matched on as as-needed basis to provide cost effective alternatives for a wide range of applications and feature preferences. Therefore, the invention is not limited to any particular combination of features.

In view of the foregoing, it will be appreciated that the present invention avoids the drawbacks of prior methods for implementing antenna downtilt and sidelobe reduction. The specific techniques and structures for implementing antenna downtilt and sidelobe reduction, and thereby accomplishing the advantages described above, will become apparent from the following detailed description of the embodiments and the appended drawings and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of a remotely controlled vertical electrical downtilt antenna deployed as a wireless base station antenna.

FIG. 2 is a diagram illustrating a vertical electrical downtilt antenna with an adjustable tilt bias.

FIG. 3 is a functional block diagram of a vertical electrical downtilt antenna.

FIG. 4 is a conceptual illustration of a variable power divider for use in the variable electrical downtilt antenna.

FIG. 5A is an electrical schematic diagram of a beam forming network for use in the variable electrical downtilt antenna.

FIG. 5B is a perspective end view of a double-sided, edge mounted module design for the beam forming network.

FIG. 5C is a side view of a first transmission media circuit of the double-sided, edge mounted beam forming network module.

FIG. 5D is a side view of a second transmission media circuit of the double-sided, edge mounted beam forming network module.

FIG. 6A is a conceptual illustration of a power distribution network for a twelve element antenna array.

FIG. 6B is a conceptual illustration of a power distribution network for a sixteen element antenna array.

FIG. 7A is a conceptual illustration of a power distribution network for a twelve element antenna array including outer sub-arrays having more antenna elements then inner sub-arrays.

FIG. 7B is a conceptual illustration of a power distribution network for a sixteen element antenna array including outer sub-arrays having more antenna elements then inner sub-arrays.

FIG. 8 is a perspective exploded view of a vertical electrical downtilt antenna.

FIG. 9 is a front view of a main panel for a vertical electrical downtilt antenna.

FIG. 10 is a perspective view of the top side of a beam steering circuit attached to a section of an antenna backplane.

FIG. 11 is a perspective view of the bottom side of the beam steering circuit attached to a section of an antenna backplane.

DETAILED DESCRIPTION OF THE EMBODIMENTS

The present invention may be embodied in a number of antenna features for implementing vertical electrical downtilt and sidelobe reduction for wireless base station antenna systems. Although these antenna systems are specifically designed for deployment as wireless base station antennas, the various features of the invention may be used in other applications, such as satellite communication systems, military radar, military communication systems, and any other beam steering application. However, these applications may exhibit different cost and performance considerations that may militate in favor of different, and potentially more sophisticated, beam steering and sidelobe reduction approaches. In addition, many additional antenna features may be implemented in connection with the antenna features described below. However, each of these modifications might add cost and complexity to the system. Therefore, it should also be appreciated that the preferred embodiments described below are presently believed to embody the most technically

and economically feasible vertical electrical downtilt antennas for many wireless base station applications.

In particular, the specific antenna embodiments descried below are dual-polarization panel antennas having a single vertical column of antenna elements. For this configuration, the beam tilting equipment effects variable beam downtilt with a downward tilt bias, which is desirable for most wireless base station applications. However, the tilt orientation could be readily modified to azimuth or any other desired tilt plane. In addition, the antenna elements need not be dual-polarization, and need not be organized into a single vertical column. For example, the antenna element spacing configuration could include multiple vertical columns, one or more rows, or any other spacing desired alternative. Again, however, a panel antenna having a single vertical column of dual-polarization antenna elements is presently considered to be the most technically and economically feasible alternative for vertical electrical downtilt antennas for wireless base station applications.

The specific antenna embodiments descried below also include advantageous design features implemented within the variable power divider, the beam forming network, and the power distribution network. These design features may be provided in various combinations and permutations to suit particular applications and feature preferences. Therefore, the invention should not be limited to any particular combination of features except as stated in the claims.

Turning now to the figures, in which like numerals refer to similar elements throughout the several figures, FIG. 1 is a block diagram of a remotely controlled vertical electrical downtilt antenna **10** deployed as a wireless base station antenna. This antenna is equipped to perform vertical electrical downtilt of a beam **12** emitted by the antenna. More specifically, the antenna **10**, which is typically mounted to a pole **14**, tower, building or other suitable support structure, includes an upright panel that supports a number of antenna elements. These antenna elements emit the beam **12** in a boresight direction **15** (shown in FIG. 2), which is the natural propagation direction of the beam when the signals emitted by the antenna elements are in phase. In the particular example shown in FIGS. 1 and 2, the antenna **10** is mounted with its main panel oriented vertically, which generally results in a horizontal boresight direction. This is a typical mounting configuration for a wireless base station antenna.

From the horizontal boresight direction **15**, some mechanism is typically provided to direct the beam **12** downward toward the horizon. It is also desirable to

have adjustable beam downtilt so that the beam can be pointed toward a desired geographical coverage area where the beam will be received with appropriate strength and to discriminate against the transmission of signals to areas generally beyond the geographical coverage area. The antenna **10** is reciprocal and the properties of the antenna in a reception mode of operation are the same as for a transmission mode at each frequency in the operational band of frequencies. The antenna **10** is configured to implement adjustable beam downtilt within a range Θ_r that extends between two boundary beam pointing directions, Θ_1 and Θ_2. The tilt range range Θ_r is also typically biased downward from the boresight direction. For example, the upper tilt boundary is typically set toward or just below horizontal, and the tilt range Θ_r typically extends to about five degrees downward. For example, tilt ranges from one to five degrees from horizontal, and from two to seven degrees from horizontal are typical for antenna arrays having twelve or more radiating elements. However, the selection of the tilt bias and tilt range is a design choice that may be changed from application to application.

In addition, the tilt bias may be fixed or adjustable. FIG. 2 illustrates the adjustable tilt bias alternative by showing three tilt bias angles for the antenna **10**. For an antenna with an adjustable tilt bias, this parameter may altered manually or mechanically, and it may be controlled locally or remotely.

Referring again to FIG. 1, the beam tilt bias and the tilt angle within the adjustable tilt range may be controlled is several different ways. For example, one or more control knobs may be located on the antenna **10** itself, typically on the rear of the main panel. However, climbing the pole **14** to adjust the beam tilt may be inconvenient. Therefore, a local controller **16** may be located at a suitable location, such as the base of the pole or with the base transceiver station **18 (BTS)**. In this case, a motor, such as a servo or stepper motor, drives the tilt control in accordance with control signals from the local controller **16**. The motor is typically mounted to the rear of the main panel of the antenna **10**, but could be located in any other suitable location. In addition, a remote controller **20** may be used to remotely control the beam tilt. For example, the remote controller **20** is typically connected to the local controller **16** by way of a telephone line **22** or other suitable communication system. The local and remote controllers may be any suitable control device, as are well known in the art.

FIG. 3 is a functional block diagram of the antenna **10**, which includes a beam steering circuit that includes a variable power divider **30** and a multi-beam beam

forming network **40**. The variable power divider **30** divides a voltage signal **32** into two complimentary amplitude voltage drive signals, which provide inputs to the multi-beam beam forming network **40** (BFN). The beam forming network **40**, in turn, produces beam driving signals **42** that are transmitted by a power distribution network **60** to a multi-element antenna array **50**. The power distribution network **60** divides each beam driving signals as appropriate for delivery to an associated sub-array of the multi-element antenna array **50**. The power distribution network **60** also includes tilt bias phase shifters **44** and phase blurring phase shifters **45**, which manipulate the phase characteristics of the beam steering signals in a coordinated manner through transmission media trace length adjustment to implement beam tilt and sidelobe reduction.

The variable power divider **30** receives and divides a voltage signal **32** into two voltage drive signals V_1 and V_2. The voltage signal **32** typically contains encoded mobile communications data and is provided through a coaxial cable that attaches to a connector on the antenna **10**, as is well known in the art. FIG. 4 is a conceptual illustration of the variable power divider **30**, which is described in greater detail in commonly owned United States Patent Application Serial Number 10/290,838 entitled "Variable Power Divider" filed on November 8, 2002, which is incorporated herein by reference. The variable power divider **30** uses a single adjustable control element **34**, typically a microstrip wiper arm, to divide the input voltage signal **32** into the voltage drive signals V_1 and V_2, which have complimentary amplitude over the range of voltage amplitude division.

More specifically, the amplitudes of sum of V_1 and V_2 sum to the amplitude input voltage signal **32**, and vary inversely with each other as the power is divided between them. In particular, the power division ranges from 100% to V_1 and zero to V_2 when the adjustable control element **34** is in the position labeled "B" on FIG. 4 to zero to V_1 and 100% to V_2 when the adjustable control element **34** is in the position labeled "C" on FIG. 4. In addition, the power division varies smoothly between these two extremes as the adjustable control element **34** is moved between the positions "B" and "C" with position "A" representing the 50% division point.

In addition to having complimentary amplitude, the voltage drive signals V_1 and V_2 exhibit matched phase (i.e., they continuously have substantially the same phase) and substantially constant phase delay through the variable power divider **30**. In other words, the phase characteristics of the voltage drive signals V_1 and V_2 with respect to each other, and with respect to the input voltage signal **32**, remains

substantially constant as the power division varies through the range of power division. An actuator **36**, such as a control knob or motor, is used to move the adjustable control element **34**, which in turn causes adjustment of the beam tilt. This is illustrated in FIGS. 3 and 4, in which the beam tilt position labeled "A" in FIG. 3 corresponds to the position "A" of the adjustable control element **34** shown in FIG. 4; the beam tilt position labeled "B" in FIG. 3 corresponds to the position "B" of the adjustable control element **34** shown in FIG. 4; and the beam tilt position labeled "C" in FIG. 3 corresponds to the position "C" of the adjustable control element **34** shown in FIG. 4.

Referring again to FIG. 3, the voltage drive signals V_1 and V_2 provide input signals to the multi-beam beam forming network **40**, which is typically configured as an orthogonal two-by-four beam forming network or a four-by-four Butler matrix with two of the input ports shunted to ground through impedance matching resistors. FIGS. 5A-D illustrates the later configuration. Both configurations, along with a number of other signal processing modules, are described in detail in commonly owned United States Patent Application Serial Number ____________________ entitled "Double-Sided, Edge-Mounted Stripline Signal Processing Modules And Modular Network" filed on July 18, 2003, which is incorporated herein by reference. Although the beam forming network **40** need not be configured as a double-sided, edge-mounted module, this configuration results in may advantages.

It should be appreciated that the number of outputs of the beam forming network **40** typically corresponds to the number of antenna sub-arrays, and may therefore be altered in accordance with the needs of a particular application. Although antennas with four and eight sub-arrays are common, other configurations, such as three, five and six sub-arrays are also typical. Of course, any desired number of sub-arrays and a wide variety of beam forming networks may be accommodated.

It is presently believed that a seven-layer modular PC board construction works best for the beam forming network modules **40**. This configuration includes a multi-layer, double-sided stripline module having a first outer ground plane layer, followed by a dielectric layer, followed by a first stripline circuit layer, followed by a dielectric layer, followed by a center ground plane layer, followed by a dielectric layer, followed by a second stripline circuit layer, followed by a dielectric layer, followed by a second outer ground plane layer. That is, the preferred board configuration includes the structure illustrated in FIGS. 5B with additional dielectric covers carrying outer ground planes adhered to the outer sides **52** and **54** of the module**40**. Addingdielectric

covers carrying outer ground plane layers reduces radiation loss and interference in the stripline transmission media circuits **56A-B**.

The beam forming network **40** of this particular antenna **10** outputs four beam driving signals **42** that each include a component from each of the voltage drive signals V_1 and V_2. Each beam driving signal, in turn, feeds one sub-array of the antenna array **50**. The power distribution network **60** connects the output ports of the beam forming network **40** to the antenna elements of the antenna array **50**.

The antenna array **50** includes a vertical column of dual-polarization antenna elements, as shown in FIG 8. The vertical column is typically divided into sub-arrays as shown in FIGS. 6A-B and 7A-B. The use of sub-arrays is typical for a wireless base station antenna configured to implement vertical electrical downtilt due to the range of variable beam tilt generally needed. It should be appreciated that the techniques described above may be used to control beam tilt in any desired direction, and that the antenna array **50** may be of any desired configuration, such as a row, multiple rows, multiple columns, a three-dimensional special arrangement, or any other desired multi-element configuration. It should also be appreciated, however, that a single column of a relatively small number of antennal elements, such as twelve or sixteen, divided into a relatively small number of sub-arrays, such as four, results in a cost effective antenna with sufficient vertical electrical downtilt and sidelobe reduction for many wireless base station applications.

The power distribution network **60** is typically configured as microstrip transmission media segments etched onto a dielectric PC board substrate. The beam forming network **40** drives two component beams "B" and "C" which vary in power with the voltage power division. That is, the component beam "B" corresponds to the voltage drive signal V_1 and the component beam "C" corresponds to the voltage drive signal V_2. Therefore, beam "B" is emitted when the voltage drive signal V_1 receives 100% of the power (i.e., corresponding to wiper arm position "B" shown on FIG. 4), and beam "C" is emitted when the voltage drive signal V_2 receives 100% of the power (i.e., corresponding to wiper arm position "C" shown on FIG. 4). When the power is split between the voltage drive signals V_1 and V_2, the component beams combine to produce a composite beam located between the component beams, as represented by beam "A." The pointing direction of the composite beam "A" thus varies between directions "B" and "C" with the power division between the voltage drive signals V_1 and V_2. Tilting a composite beam in the manner described above advantageously produces lower sidelobes than a single-component beam steered through

conventional phase control using the same number of control devices. The sidelobes of the component beams partially cancel each other as they combine to form the composite beam. Driving different and variable signals to, for example, four sub-arrays typically is accomplished using three control devices (i.e., a number being one less than the number of sub-arrays) when conventional phase shifting approaches are used. Hence, the method defined herein advantageously reduces the number of control devices needed to drive different and variable signals to sub-arrays of an array antenna for he purpose of downtilting a beam.

In view of the preceding, it should be understood that increasing the number of antenna sub-arrays and increasing the spacing between the antenna elements and/or the sub-arrays are generally effective at producing further sidelobe reduction. However, the cost associated with these design changes must be weighed against the additional benefit to be obtained. It should also be appreciated that providing a relatively small antenna array emitting a composite beam, as taught in this specification, is generally a more cost effective method of implementing side lobe reduction than conventional methods applied to single-component beams, such as increasing the antenna element spacing and deploying multiple columns of antenna elements, which results in a larger antenna array. It should also be appreciated that providing a range of downtilt that spans an extent that is approximately equal to one half-power beam width of the antenna using one control device is advantageous in simplicity and cost.

Still referring to FIG. 3, the lengths of the microstrip transmission media trace segments of the power distribution network **60** connecting the outputs of the beam forming network **40** with the antenna elements **50** are nominally selected to cause the signals to be in phase when they reach the antenna elements, which produces a beam pointed in the boresight direction of antenna. To offset the beam direction from the boresight direction, tilt bias phase shifters **44** are included in the transmission media traces for the beam drive signals **42**. Fixed phase tilt bias phase shifters can be implemented through trace length adjustments to implement a desired fixed beam tilt bias. Additionally or alternatively, variable phase shifters may be use to provide a variable tilt bias, as illustrated in FIG. 2.

A common actuator **46** may be used to drive the adjustable tilt bias phase shifters **44** in a coordinated manner. For example, a toothed rack may drive common pinion gears that, in turn, drive similar extension arms of trombone-type or wiper-type

microstrip or other suitable phase shifters. The actuator may be manual, such as a knob, or motorized, and may be controlled locally or remotely, as shown on FIG. 1.

In addition, one or more of the sub-arrays may include one or more antenna element phase shifters **45** to slightly alter the phase signal delivered to the elements of the sub-array. That is, an individual phase shifter is typically located within the transmission media trace feeding an associated antenna element. These phase shifters are designed to slightly mismatch or "blur" the phase matching of the signals emitted by antenna elements of the associated sub-arrays for the purpose of reducing sidelobe emission. In particular, the phase matching of the signals emitted by outer sub-arrays may be blurred a bit more severely than the signals emitted by the inner sub-arrays for the purpose of further reducing sidelobe emission.

The antenna element phase shifters **45** are typically implemented through transmission segment length adjustment. However, other types of phase shifters may be used. In particular, phase shifters implemented through transmission segment length adjustment impose fixed phase shifts. Alternatively, adjustable antenna element phase shifters may be used, which may be locally or remotely controlled. However, cost considerations may favor implementing the antenna element phase shifters **45** through fixed length transmission segment adjustments. FIG. 6A is a conceptual illustration of the power distribution network **60** feeding the antenna array **50.** This particular embodiment includes a vertical column of twelve antenna elements organized into two outer sub-arrays **62A-B** and two inner sub-arrays **62A-B** that each include three antenna elements. Each sub-array is fed by an associated one of the beam driving signals **42**. The antenna includes adjustable tilt bias phase shifters **44** and fixed phase blur phase shifters **45**, as described previously with reference to FIG. 3. FIG. 6B is a conceptual illustration of a similar sixteen element antenna array design including two outer sub-arrays **68A-B** and two inner sub-arrays **69A-B** that each include four antenna radiating elements. The twelve and sixteen element designs shown in FIGS. 6A-B are believed to be suitable for use as wireless base station antennas.

FIG. 7A is an alternative design for a twelve element antenna array including two outer sub-arrays **72A-B** that each include four antenna elements, and two inner sub-arrays **74A-B** that each include three antenna elements. Having outer sub-arrays with more antenna elements than the inner sub-arrays reduced the relative power delivery to the individual elements of the outer sub-arrays **72A-B**. This has the effect of reducing the sidelobe emission of the antenna. FIG. 7B is a similar alternative

antenna design for a sixteen element antenna array including two outer sub-arrays **76A-B** that each include five antenna elements, and two inner sub-arrays **78A-B** that each include three antenna elements. Again, the twelve and sixteen element designs shown in FIGS. 7A-B are believed to be suitable for use as wireless base station antennas.

FIGS. 8-11 are computer-aided design (CAD) to-scale illustrations of a particular commercial embodiment of the vertical electrical downtilt antenna **80** shown in FIG. 6A, which includes twelve dual-polarization antenna elements **82**. This antenna is designed for an operational carrier frequency of 1.92 GHz (which is the center frequency of the authorized US Personal Communication Services, PCS, wireless band), and the antenna elements are spaced 0.7 free-space wavelength apart, which is approximately 4.6 inches. The electrically conducting backplane **84** for this antenna is rectangular with dimensions 56 inches long by 8 inch wide [approximately 142cm by 20cm]. A sixteen element antenna is correspondingly longer, 72 inches long by 8 inches wide [approximately 183cm by 20cm] to accommodate four additional antenna elements with the same spacing. The radome **86** fits over and attaches to the backplane.

The antenna **80** includes two mounting brackets **88A-B**, two coaxial cable antenna interface connectors **90A-B**, and an actuator knob assembly **92** that connect to the rear side of the backplane **84**. The coaxial cable connectors **90A-B** receive coaxial cables supplying two input voltage signals **32** (shown on FIG. 3), one for each polarization of the dual-polarization antenna. A conducting ground planeon the underside of a main panel dielectric **96** is attached with a non-conducting adhesive **94** to the front side of the backplane **84**. The conducting ground plane of the main panel printed circuit (PC) board **96** is capacitively coupled to the backplane **84** for RF signal flow across the junction. The main panel **96** is a dielectric PC board etched with tin-coated copper traces that form transmission media segments carrying the voltage signals from the coaxial cables connectors **90A-B** to the antenna elements **82**. More specifically, the transmission media segments form two virtually identical beam steering and power distribution circuits **98A-B**, one for each polarization.

The dielectric material of the main panel **96** may be PTFE Teflon®, a laminate impregnated with glass fibers, having a dielectric constant equal to 2.2 ($\varepsilon_r = 2.2$). This material can be used to construct PC boards that will exhibit an effective dielectric constant of 1.85 ($\varepsilon_{reff} = 1.85$) for microstrip transmission media segments exposed to the PC board on one side and exposed to air on the other side. For this type of PC

board circuit, the wavelength in the guide (λ_g) (i.e., the wavelength as propagating in the microstrip transmission media as laid out on the PC board with one side exposed to the dielectric substrate and the other side exposed to air) is approximately 4.52 inches [11.48 cm].

Referring to FIGS. 3 and 4 as well as FIG. 8, two variable power dividers **102A-B** (one for each polarization -- element **30** on FIG. 3) and two power distribution networks **104A-B** (one for each polarization -- element **60** on FIG. 3) are located on the main panel **96**, whereas two beam forming networks **106A-B** (one for each polarization -- element **40** on FIG. 3) are implemented as double-sided, edge-mounted modules that are solder-connected to the main panel **96**. Two wiper arms **108A-B** (one for each polarization -- element **34** on FIG. 4) are pivotally attached to the variable power divider areas of the main panel **96**. The wiper arms **104A-B** are formed on small dielectric PC boards with etched copper traces similar to the materials used to construct main panel (but without a ground plane), and are mechanically coupled to each other through dove-tail gears formed into rear portions of the wiper arms. This allows both wiper arms to be moved in a coordinated manner by the single actuator knob **92** (element **36** on FIG. 3). In motorized embodiments, the actuator knob assembly **92** is replaced by a small motor and mechanical drive, such as a servo or stepper motor, mounted to rear of the backplane **84**. The motor may be housed in a suitable enclosure and attended typically with an electronics PC board assembly associated with electrical power and motor control.

In addition, for embodiments including variable tilt bias, a rack and pinion drive system with a separate motor is typically attached to the rear side of the backplane **84**. As noted previously, the tilt bias phase shifters may be implemented as gear-driven, trombone-type or wiper-type phase shifters, which are distributed in two rows (one for each polarization) along the main panel **96**. In addition, a single toothed rack moved by a single knob or motor driven gear can typically be used to turn all of the tilt bias phase shifters in a coordinated manner so that all of the antenna elements for both polarizations are tilt biased in a coordinated manner.

FIG. 9 is a front view of the main panel **96**. One of the antenna elements **82** is labeled for reference. The variable power dividers **102A-B** and the power distribution networks **104A-B** are shown a bit more clearly in this view. The wiper arms **108A-B** are shown in the center of the main panel **96** but have not been labeled to avoid obscuring the figure. The beam forming modules **106A-B** are difficult to see in this view because they are edge mounted to the main panel **96**.

FIG. 10 is a perspective view of the top side of the section of the antenna carrying the beam steering circuit, which includes the variable power dividers **102A-B** and the beam forming modules **106A-B**. This illustration provides a better view of the beam forming modules **106A-B** and the wiper arms **108A-B**. FIG. 11 is a perspective view of the bottom side of this same section of the antenna, which shows the cable connectors **90A-B** and the control actuator **92**.

Although this particular antenna does not include the variable tilt bias feature, it is configured to implement a downtilt bias of approximately 4.5 degrees with a tilt range from two to seven degrees. This is accomplished by varying the lengths of the transmission media trace legs to the antenna element of the sub-arrays using a center pivot method. Specifically, the trace length adjustments from the nominal in-phase length can be expressed in terms the wavelength in the guide λ_g (in this particular embodiment about 4.52 inches [11.48cm]) as follows:

First (top) sub-array trace length adjustment = 108.337 degrees;
Second sub-array trace length adjustment = 36.112 degrees;
Third sub-array trace length adjustment = -36.112 degrees; and
Fourth (bottom) sub-array trace length adjustment = -108.337 degrees.

In addition, this particular antenna is configured to implement phase blurring as described with reference to FIG.3 as follows:

first (top) sub-array, first (top) element trace length adjustment = 30 degrees
first sub-array, second element trace length adjustment = 0 degrees
first sub-array, third element trace length adjustment = -30 degrees
second sub-array, first element trace length adjustment = 15 degrees
second sub-array, second element trace length adjustment = 0 degrees
second sub-array, third element trace length adjustment = -15 degrees
third sub-array, first element trace length adjustment = 15 degrees
third sub-array, second element trace length adjustment = 0 degrees
third sub-array, third element trace length adjustment = -15 degrees
fourth (bottom) sub-array, first element trace length adjustment = 30 degrees
fourth sub-array, second element trace length adjustment = 0 degrees
fourth sub-array, third element trace length adjustment = -30 degrees

An alternative tilt bias and element phase shift for this antenna is as follows:

First (top) sub-array trace length adjustment = 101.25 degrees;
Second sub-array trace length adjustment = 33.75 degrees;
Third sub-array trace length adjustment = -33.75 degrees; and
Fourth sub-array trace length adjustment = -101.25 degrees.

first (top) sub-array, first (top) element trace length adjustment = 33.75 degrees
first sub-array, second element trace length adjustment = 0 degrees
first sub-array, third (bottom) element trace length adjustment = -33.75 degrees
second sub-array, first element trace length adjustment = 16.875 degrees
second sub-array, second element trace length adjustment = 0 degrees
second sub-array, third element trace length adjustment = -16.875 degrees
third sub-array, first element trace length adjustment = 16.875 degrees
third sub-array, second element trace length adjustment = 0 degrees
third sub-array, third element trace length adjustment = -16.875 degrees
fourth sub-array, first element trace length adjustment = 33.75 degrees
fourth sub-array, second element trace length adjustment = 0 degrees
fourth sub-array, third element trace length adjustment = -33.75 degrees

For a sixteen element array with similar element spacing, a 3 degree tilt bias with phase blurring can be implemented is as follows:

First (top) sub-array trace length adjustment = 122.062 degrees;
Second sub-array trace length adjustment = 34.87 degrees;
Third sub-array trace length adjustment = -34.87 degrees; and
Fourth (bottom) sub-array trace length adjustment = -122.062 degrees.

first (top) sub-array, first (top) element trace length adjustment = 67.5 degrees
first sub-array, second element trace length adjustment = 22.5 degrees
first sub-array, third element trace length adjustment = -22.5 degrees
first sub-array, fourth (bottom) element trace length adjustment = -67.5 degrees
second sub-array, first element trace length adjustment = 16.875 degrees
second sub-array, second element trace length adjustment = 5.635 degrees
second sub-array, third element trace length adjustment = -5.625 degrees
second sub-array, fourth element trace length adjustment = -16.875 degrees
third sub-array, first element trace length adjustment = 16.875 degrees
third sub-array, second element trace length adjustment = 5.625 degrees

third sub-array, third element trace length adjustment = -5.625 degrees
third sub-array, fourth element trace length adjustment = -16.875 degrees
fourth (bottom) sub-array, first element trace length adjustment = 67.5 degrees
fourth sub-array, second element trace length adjustment = 22.5 degrees
fourth sub-array, third element trace length adjustment = -22.5 degrees
fourth sub-array, fourth element trace length adjustment = -67.5 degrees

In view of the foregoing, it will be appreciated that present invention provides significant improvements for implementing vertical electrical downtilt and sidelobe reduction for wireless base station antennas. It should be understood that the foregoing relates only to the exemplary embodiments of the present invention, and that numerous changes may be made therein without departing from the spirit and scope of the invention as defined by the following claims.